# THE CORRECTED LOG N-LOG FLUENCE DISTRIBUTION OF COSMOLOGICAL $\gamma$-RAY BURSTS

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Recent analysis of relativistically expanding shells of cosmological $\gamma$-ray bursts standard and not peak luminosity ($L_0$). Assuming a flat Friedmann cosmology ($q_o = 1/2$, $\Lambda = 0$) and constant rate density ($\rho_0$) of bursting sources, we fit a standard candle energy to a uniformly selected log $N$-log $S$ in the BATSE 3B catalog correcting for fluence efficiency and averaging over 48 observed spectral shapes. We find the data consistent with $E_0 = 7.3^{+0.7}_{-1.0} \times 10^{51}$ ergs and discuss implications of this energy for cosmological models of $\gamma$-ray bursts.

## INTRODUCTION

On the basis of strong threshold effects of detectors, Klebesadel, Fenimore, and Laros (1982) concluded that GRB fluence tests were largely inconclusive. As a result, nearly all subsequent number-brightness tests have used peak flux ($P$) rather than fluence ($S$). However, the standard candle peak luminosity assumption that is required by log $N$-log $P$ studies is unphysical. If, for instance, bursts originate at cosmological distances and are produced by colliding neutron stars (11) then one might expect that total energy would be standard and not peak luminosity. Moreover, recent analysis of the time histories in relativistically expanding shell models has found the required differences in bulk $\Gamma$ factor between different GRBs all but eliminates the possibility of a standard candle luminosity in such models (9).

In this paper, we seek to eliminate the large threshold effects present in log $N$-log $S$ studies by correcting the observed number of bursts at a given fluence by the trigger efficiency of the detector. In §I we use the calculated trigger efficiency in PVO (6) and the catalogue of PVO events (4) to test the correction algorithm. In §II we examine the fitting algorithm to the log $N$-log $S$ curve in BATSE 3b and find a standard candle energy for cosmological gamma-ray bursts. In §III we discuss the implications of such an energy and the distances implied by the fit.

## I. PVO CONSISTENCY CHECK

The Pioneer Venus Orbiter (PVO) had a peak flux trigger system (sampled on 0.25, 1.0, and 4.0 sec timescales) and was sensitive to bursts down to fluxes

of $5 \times 10^{-6}$ erg cm$^{-2}$. Despite a substantially lower fluence trigger sensitivity range, PVO saw hundreds more bright bursts than BATSE due the relatively long on-time and large sky-coverage of PVO. As the bright region of the BATSE log $N$-log $S$ curve seems to fit a -3/2 power law well, we would expect that the entire log $N$-log $S$ curve of PVO should show a similar behavior.

Using the PVO trigger efficiency, $\epsilon(S)$, from in t' Zand & Fenimore (1996), for each burst $i$ with fluence $S_i$ in the PVO catalogue we take the expected number of bursts with pre-detection fluence to be $N_{i,\mathrm{true}} = N_{i,\mathrm{obs}}/\epsilon(S_i)$. We then compare the derived log $N(> S)$-log $S$ curve with a -3/2 power law with arbitrary $S$-intercept as seen in figure (1b). Although at lower fluence there appears to be a deviation from -3/2, the fit is good: with a Kolmogorov-Smirnov (KS) probability of 40% that the corrected distribution comes from a -3/2 power law. We derive this KS statistic by finding the maximum distance between the corrected and -3/2 distributions (in linear space) down to $S = 10^{-4.5}$ erg cm$^{-2}$, the fluence at which $\epsilon(S)$ falls to 50%. By comparing the distributions down to lower fluences, we find an even better KS fit. This is understandable because as we add more bursts to the distribution, small deviations at high fluences contribute less to the KS distance parameter. Note that although the fit is acceptable, a -3/2 slope is not necessarily required by the corrected data. We thus conclude that the trigger efficiency determination algorithm from in t' Zand and Fenimore (1996) is sound, at least in PVO.

## II. Deriving the log N-log S Curve

### A. BATSE Trigger Efficiency

One subtly worth noting is that BATSE trigger efficiencies are model dependent, ie. they depend on the choice of $E_0$ and cosmology, since it is necessary to know *a priori* the true underlying distribution of bursts that passes by the detector.

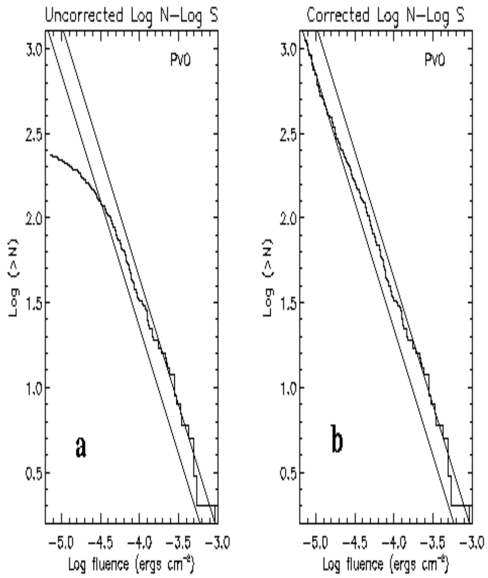


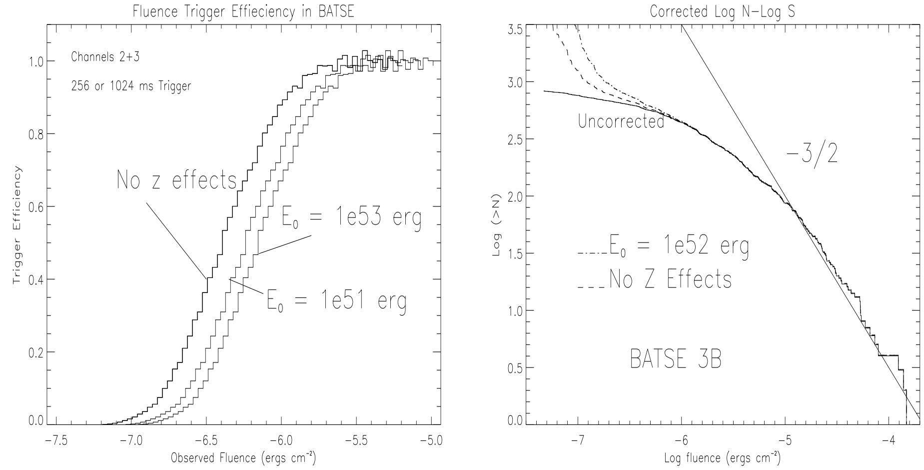

**FIG. 1** The log $N$-log $S$ curve for PVO. a) The uncorrected curve for 293 events in the PVO catalogue which shows significant departure (KS $\simeq$ 0.0) from the -3/2 power law (shown as solid line) expected from BATSE observations. b) The corrected curve (KS = 0.40 at $\epsilon(S)$ = 0.50) using the PVO trigger efficiency from in t' Zand & Fenimore (1996). Any deviation from a -3/2 power-law at low fluences we attribute to an incomplete understanding of the trigger efficiency.

In fact, the derivation of the PVO $\epsilon(S)$ assumed an underlying -3/2 distribution. Petrosian and Lee (1996) have constructed trigger efficiencies using bivariate correlation. While this method does not assume a particular cosmology, it does require that GRB brightness and duration are inherently uncoupled. Our method does not have this requirement and we make no assumptions about the bursts other then they are cosmological in origin. The BATSE trigger efficiencies could be calculated for any $E_0$ ($q_0 = 1/2$, $\Lambda = 0$) and two are depicted in figure (2a). Note that the efficiency is nearly unity for the several orders of magnitude in fluence. The corrected log $N$-log $S$ curve for BATSE is depicted in figure (2b) for two values of $E_0$. Interestingly, the two distributions are nearly identical for most of the fluence range. In addition, it is clear that the bend from -3/2 in log $N$-log $S$ is true.

### B. Standard Candle Energy Fits

The observed fluence of a source depends strongly on the spectrum, and since the observed spectral shape depends on the distance to the object, the intrinsic spectrum of a GRB object must be used. In addition, the normalization and the spectral shape vary over the duration of the burst, adding to the uncertainty in analysis.

Following a similar analysis as in Fenimore and Bloom (1995), we take as our baseline spectra averages over the GRB spectra fit by Band et al. (1993). Each such baseline burst has associated with it an observed fluence, $S_i$, and an observed spectral shape, $\phi_i(E)$.




a b

**FIG. 2:** a) The BATSE trigger efficiency for different $E_0$ and b) the corrected log $N$-log $S$ curve for 830 BATSE bursts. Along with the uncorrected log $N$-log $S$ curve, we depict a corrected curve corresponding to an assume standard candle energy of $E_0$ of $10^{52}$ ergs (dot-dash line) and a corrected curve where the effect of redshift on the baseline spectra is removed (dash line).

Since each Band et al. (1993) burst spectrum is averaged over the duration of the burst, we assume in the following analysis that the spectral shape is constant, that is, $\phi(E, t_s) \simeq N(t_s)\phi_i(E)$. The fluences, $S_i$ [ergs cm$^{-2}$], are available for 48 of the Band et al. (1993) bursts in BATSE 3B (10).

The observed spectral shape, $\phi_i(E)$, will not necessarily come from a burst at $z \sim 0$ especially if $E_0$ is large. Therefore, for a given $E_0$, $S_i$, and $\phi_i(E)$ we first solve for the redshifts, $z_i$, of the baseline events associated with each spectral shape. The standard candle energy, $E_0$, is given by,

$$E_0 = 4\pi R_{i,z}^2 \int_0^\infty N(t_s)dt_s \int_{30}^{2000} E\phi_i\left(\frac{E}{1+z_i}\right)dE \tag{1}$$

where $N(t_s)$ is the normalization of the spectrum (units of ergs keV$^{-1}$) as a function of time at the source. The comoving distance, $R_{i,z}$, is defined in eq. [2] of Fenimore & Bloom (1995). The energy range used in calculating $E_0$ in eq. (1) is taken as 30-2000 keV, since we later compare $E_0$ to standard candle peak luminosity found in the same energy band.

The observed fluence of the i$\underline{th}$ baseline burst in the energy range 50-300 keV is given by,

$$S_i = \int_0^\infty N(t_{obs})dt_{obs} \int_{50}^{300} E\phi_i\left[\frac{1+z_r}{1+z_i}E\right]dE, \tag{2}$$

where $N(t_{obs})$ is the observed normalization of the spectrum.

For a given standard candle energy, $E_0$, we numerically determine the redshift $(1+z_i)$ of the i$\underline{th}$ baseline burst using eqs. (1, 2) and letting $z_r = z_i$. Note that $(1+z_i)\int N(t_s)dt_s = \int N(t_{obs})dt_{obs}$.

**TABLE 1.** Best Fit Distribution of $E_0 = 7.0 \times 10^{51}$ ergs

| | Fluence Ranges[a] (50-300 keV) | | $\Delta N[S_j$ to $S_{j+1}]$ | | |
|---|---|---|---|---|---|
| Bin Number($j$) | $S_j$ | $S_{j+1}$ | Observed[b] | Predicted | $1+z_j$ |
| 1 | 2.16e-07 | 3.82e-07 | 51 | 38.4 | 3.88 |
| 2 | 3.82e-07 | 5.85e-07 | 42 | 50.5 | 3.24 |
| 3 | 5.85e-07 | 7.55e-07 | 42 | 36.3 | 2.84 |
| 4 | 7.55e-07 | 1.13e-06 | 46 | 63.0 | 2.64 |
| 5 | 1.13e-06 | 1.43e-06 | 37 | 36.8 | 2.36 |
| 6 | 1.43e-06 | 2.00e-06 | 48 | 49.7 | 2.22 |
| 7 | 2.00e-06 | 2.80e-06 | 39 | 44.3 | 2.04 |
| 8 | 2.80e-06 | 4.05e-06 | 44 | 41.1 | 1.89 |
| 9 | 4.05e-06 | 6.20e-06 | 37 | 37.2 | 1.74 |
| 10 | 6.20e-06 | 1.36e-05 | 40 | 44.7 | 1.60 |
| 11 | 1.36e-05 | 6.60e-05 | 41 | 32.3 | 1.41 |

[a] In ergs cm$^2$

[b] Bursts with $C_{min}/C_{max} > 1$ on the 256 or 1024 ms timescale in BATSE 3b.

Instead of assuming a spectral shape at the source, we use an average over baseline spectra to compute the number of expected observed bursts, $\Delta N_{exp}[S_j \text{ to } S_{j+1}]$ in some fluence range $[S_j, S_{j+1}]$:

$$\Delta N_{exp}[S_j \text{ to } S_{j+1}] = \frac{4\pi}{N_{BAND}} \sum_{i=1}^{N_{BAND}} \int_{R(S_j)}^{R(S_{j+1})} \epsilon[S_i(r)] \frac{\rho_0}{1+z_r} r^2 dr. \qquad (3)$$

where $N_{BAND} = 48$ is the number of baseline spectra used and $\rho_o$ is the rate density of bursts per comoving volume. The quantity $S_i(r)$ is the predicted fluence (using eqs. [1, 2]) of the i$\underline{th}$ baseline burst if it was at a distance $r$. This distance corresponds to a redshift $1 + z_r$.

We construct 11 fluence bins (in BATSE channels 2+3 corresponding to approximately 50-300 keV) of roughly equal number of bursts. We select bursts with $C_{min}/C_{max} > 1$ on either the 256 or 1024 ms timescale, then find a minimized $\chi^2$ between the number of predicted bursts and observed by varying $E_0$. For 9 degrees of freedom we find an acceptable $\chi^2 = 14.7$ corresponding to a standard candle $E_0 = 7.3^{+0.7}_{-1.0} \times 10^{51}$ ergs. Table (1) gives the bin ranges, number of observed bursts per bin, number of predicted bursts for the best fit energy, and their implied redshifts.

## III. CONCLUSIONS

Our fit of $E_0 = 7.0^{+0.7}_{-1.0} \times 10^{51}$ [30-2000 keV] ergs seems a plausible number on the basis that GRBs last on the average 10 sec and $L_0 = 4.6 \times 10^{50}$ erg s$^{-1}$ from log $N$-log $P$ studies (2). However, this $E_0$ implies a rather large efficiency of energy conversion to $\gamma$-rays ($\sim 10\%$) if the bursting mechanism is colliding neutron stars ($M_{total} \simeq 2.8 M_\odot$). Nevertheless, this result would seem to help resolve the "no-host" problem (cf. Fenimore 1993 et al.). Interestingly, that the dimmest bursts ($S \simeq 5 \times 10^{-8}$ erg cm$^{-2}$) are required to be at a redshift of $1 + z \simeq 6.4$ given this $E_0$, would seem to rule out several cosmological models that require GRB progenitors to be within galaxies (although see Lu et al.

1996). This surprisingly high redshift is due to the correct blueshifting of the baseline spectra back to the source in eq. (1). If we neglect this factor, we obtain a smaller, more tenable redshift of the dimmest bursts ($1 + z = 5.2$).

Whatever the conclusion about the models, we note two important results. First, the bend in the log $N$-log $S$ curve in BATSE is real, not an artifact of strong threshold effects. This implies that we are seeing either a truncated spatial distribution of GRBs (as in Galactic models) or an effect due to the expansion of the universe. The bend might also be caused by a combination of rate density or number density evolution, and a study of their possible effects is certainly warranted. Secondly, with the availability of Monte Carlo modeling of trigger efficiencies, log $N$-log $S$ tests need no longer be inconclusive.

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